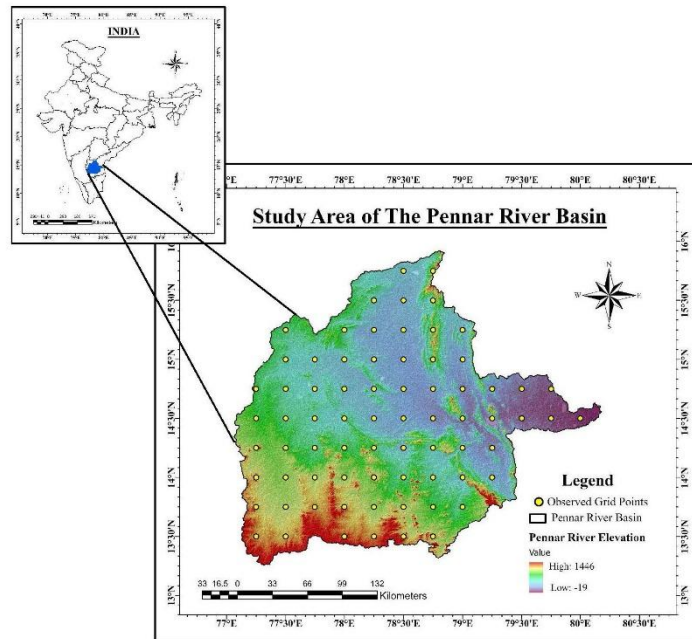


# ASSESSMENT OF HYDROLOGICAL EXTREMES AND IMPACT ON FUTURE WATER AVAILABILITY IN PENNAR RIVER BASIN UNDER CHANGING CLIMATE



**National Institute of Hydrology**  
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Jal Vigyan Bhawan, Roorkee - 247667 (Uttarakhand), INDIA

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**Final Report**

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IMPACT ON FUTURE WATER AVAILABILITY IN PENNAR  
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## PREFACE

Water availability in semi-arid river basins continues to face growing uncertainty under a changing climate. The Pennar River Basin, located in Peninsular India, represents one such vulnerable system where limited rainfall, high evapotranspiration, and strong dependence on monsoon dynamics shape water availability. In recent decades, increasing climate variability has started to influence both drought behaviour and hydrological processes in the basin, raising important concerns for long-term water resource sustainability.

This report presents a comprehensive assessment of hydrological extremes and their implications for future water availability in the Pennar River Basin. We developed this work under an internal research initiative at the National Institute of Hydrology, Roorkee, with the objective of bridging the gap between drought assessment and basin-scale hydrological response under climate change. We combined observed datasets, drought indices, and physically based hydrological modelling to build a consistent understanding of both past trends and future risks. We analysed historical drought conditions using the Standardised Precipitation Evapotranspiration Index (SPEI), which captures both rainfall deficits and atmospheric demand. This approach allowed us to represent drought behaviour in a warming climate. We further extended the analysis using Severity-Duration-Frequency (SDF) relationships to evaluate how drought characteristics evolve over time. To assess future water availability, we used a calibrated Variable Infiltration Capacity (VIC) hydrological model driven by bias-corrected climate projections from multiple CMIP6 Global Climate Models (GCMs) under SSP245 and SSP370 scenarios.

The study highlights how climate change reshapes hydrological behaviour in the Pennar River Basin. It shows that droughts are becoming more severe and persistent, while runoff increases mainly during the monsoon season. This imbalance between water availability and seasonal demand presents a major challenge for water management in the basin. We hope this report provides useful insights for researchers, planners, and decision-makers working on water resources in semi-arid regions. The findings emphasize the need to move beyond traditional approaches based on historical conditions and adopt more adaptive and forward-looking strategies.

Dr. Sunil Gurrapu (PI), Scientist 'D', Centre for Cryosphere and Climate Change Studies (C4S), has prepared this report with technical support from other team members. I acknowledge the support of the institute and the contribution of all the team members and collaborators who helped complete this report.

## Executive Summary

The study examines how hydrological extremes and water availability in the Pennar River Basin are likely to change under future climate conditions. The basin, located in a semi-arid region of Peninsular India, depends heavily on monsoon rainfall and already faces challenges related to water scarcity and variability. Even small changes in climate can significantly affect runoff, groundwater recharge, and overall water availability. In this context, we aim to understand both historical drought behaviour and future hydrological changes using a combination of observed data, drought indices and hydrological modelling.

We begin by analysing historical drought conditions using the Standardised Precipitation Evapotranspiration (SPEI), which accounts for both precipitation and evapotranspiration. This allows us to capture the full water balance rather than relying only on rainfall deficits. We evaluate drought characteristics such as severity, duration, and frequency across multiple time scales. The results show that drought behaviour in the Pennar basin has changed over time. Short-term variability dominates at the monthly scale, but longer time scales reveal more persistent and hydrologically meaningful droughts. In recent decades, droughts have become more severe, especially for longer durations that directly affect water resources. We further examine drought behaviour using Severity-Duration-Frequency (SDF) analysis. This approach helps us understand how drought severity changes with duration and return period. The results show a clear upward shift in drought severity in recent decades compared to earlier periods. This indicates that drought conditions in the basin no longer follow a stationary pattern. In simple terms, past conditions no longer provide a reliable guide for future drought risk.

To assess future drought conditions, we use projections from the five CMIP6 Global Climate Models (GCMs) under two emission scenarios: SSP245 and SSP370. We analyse two future periods: mid-century (2041-2070) and late-century (2071-2100). The results show that drought severity increases across most models and time scales, particularly at seasonal (SPEI-3) and medium-term (SPEI-6) scales. The signal becomes stronger in the late-century period, indicating that droughts will likely become more intense and persistent. Although some variability exists across models, the overall trend points towards increasing drought risk in the Pennar River Basin. We

then assess water availability using a calibrated Variable Infiltration Capacity (VIC) hydrological model. We drive the model using bias-corrected climate projections to simulate runoff and other water balance components under both historical and future conditions. The results show that runoff in the basin increases in the future, particularly during the monsoon and post-monsoon seasons. Peak flows become stronger and occur over a slightly longer period, especially under the higher emission scenario (SSP370).

However, this increase in runoff does not occur uniformly throughout the year. Most of the additional water concentrates during the monsoon months, while pre-monsoon and winter seasons show only modest increases. This creates a clear imbalance in water availability. The basin receives more water during already wet periods, but dry-season conditions do not improve significantly. As a result, water availability becomes more uneven across the year. When we compare drought and runoff results together, an important pattern emerges. The basin experiences both increasing drought severity and increasing runoff at the same time. This may seem contradictory at first, but it reflects a shift towards greater variability and more extreme conditions. The basin does not simply become wetter or drier; instead, it experiences more intense wet periods and more severe dry periods.

This shift has important implications for water management. Higher runoff during the monsoon increases the risk of flooding, while persistent droughts increase stress during dry periods. Traditional water management approaches based on historical averages may not work effectively under these conditions. The basin will need more adaptive and flexible strategies that can handle both extremes. The comparison between SSP245 and SSP370 highlights the influence of emission pathways. The higher emission scenario shows stronger increases in both drought severity and runoff, indicating that climate impacts become pronounced with greater warming. This emphasizes the importance of considering multiple scenarios in planning and highlights the benefits of climate mitigation efforts.

Overall, this study shows that climate change will significantly alter hydrological behaviour in the Pennar River Basin. The basin will face a future characterised by increased variability, stronger extremes, and greater uncertainty. Managing water resources under these conditions will require a shift towards

integrated, forward-looking approaches that combine climate projections, hydrological modelling and adaptive management strategies.

**Keywords:** Pennar River Basin; Hydrological Extremes; Climate change; SPEI; Drought Assessment; Water Availability; Semi-arid Basin

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## 1.0. INTRODUCTION

Hydrological extremes, particularly droughts and floods, have emerged as one of the most critical challenges to water resource sustainability in the context of global climate change. Increasing atmospheric temperatures have intensified the global hydrological cycle, resulting in altered precipitation regimes, enhanced evapotranspiration, and increased variability in runoff processes. These changes have significantly influenced the frequency, severity, and duration of hydrological extremes across different climatic regions (Trenberth, 2011; IPCC, 2021). Recent studies further indicate that extreme drought events have become more widespread and persistent globally since the early 21<sup>st</sup> century, with increasing occurrence of multi-year droughts even in traditionally water-abundant regions. India is particularly vulnerable to such changes due to its dependence on monsoon rainfall and the inherent variability of its climate system. The temporal and spatial variability of monsoon precipitation governs the hydrological behaviour of river basins across the country, making them highly sensitive to climatic fluctuations. Semi-arid basins in peninsular India, such as the Pennar River Basin, are especially susceptible because of limited rainfall, high evapotranspiration rates, and increasing anthropogenic pressures on water resources. In such regions, even minor changes in precipitation or temperature can lead to significant alterations in streamflow and groundwater recharge, thereby affecting overall water availability.

Hydrological extremes, commonly characterized as deviations from normal hydrological conditions include both high-flow events (floods) and low-flow conditions (droughts). Among these, drought is a complex phenomenon due to its slow onset, long duration, and cascading impacts across meteorological, agricultural, and hydrological systems. The propagation of drought from meteorological deficits to hydrological impacts often involves time lags and nonlinear interactions, which complicate its assessment and prediction. The characterization of drought typically involves the evaluation of severity, duration, and frequency, which are essential for understanding its implications for water resources. Traditional assessments of hydrological extremes have relied primarily on historical observations; however, such approaches are increasingly insufficient under changing climate conditions. Future hydrological regimes are expected to deviate significantly from historical patterns due to changes in precipitation intensity, seasonal distribution, and temperature-driven

evapotranspiration. Consequently, there is a growing need to integrate observed datasets with hydrological model simulations and climate projections to provide a more robust assessment of future water availability.

Rain gauge observations, reanalysis datasets, and satellite-derived products consistently indicate a statistically significant increase in both the frequency and intensity of dry spells across India since the late twentieth century (Kumar et al., 2014; Krishnan et al., 2020). These observed trends align with national- and global-scale assessments, which attribute the amplification of drought hazard to rising land surface temperatures, increased evaporative demand, and growing variability in the southwest monsoon system (Krishnan et al., 2020; IPCC, 2021). Such changes are particularly critical in semi-arid basins, where hydrological responses are highly sensitive to climatic variability. In this context, developing a robust, basin-specific understanding of both historical and projected hydrological extremes becomes essential for effective water resource planning and management. For regions such as the Pennar River Basin, where water availability is already constrained, such assessments are crucial for ensuring long-term sustainability under changing climatic conditions.

Drought assessment has evolved considerably with the development of various indices that capture different aspects of water deficit. The Standardized Precipitation Index (SPI) remains one of the most widely used tools for meteorological drought assessment due to its simplicity and flexibility across multiple time scales (McKee et al., 1993). However, SPI does not account for temperature effects, which are increasingly important under global warming scenarios. To address this limitation, the Standardized Precipitation Evapotranspiration Index (SPEI) incorporates both precipitation and evapotranspiration, making it more suitable for assessing drought under climate change conditions (Vicente-Serrano et al., 2010). Recent studies have demonstrated that SPEI provides improved sensitivity to warming trends and better captures drought severity in semi-arid regions (e.g. Gurrupu et al., 2014). The use of multiple drought indices has gained prominence in recent years, as single-index approaches may not adequately represent the complexity of drought processes. Studies have shown strong correlations between SPI and SPEI while also highlighting differences in their ability to capture temperature-driven effects and groundwater responses. Furthermore, integrated drought assessment frameworks combining

meteorological, hydrological, and groundwater indices have been developed to improve the representation of drought dynamics and vulnerability, particularly in semi-arid regions of India.

The Pennar River Basin, characterized by its semi-arid climate and high inter-annual variability in rainfall, presents a critical case for studying hydrological extremes and their implications for water availability. Despite its vulnerability, there is a lack of comprehensive studies that integrate historical analysis, drought assessment using multiple indices, and future projections of water availability under climate change. Addressing this gap is essential for developing sustainable water management strategies in the basin. The present study aims to evaluate historical hydrological extremes in the Pennar River Basin using both observed records and model-simulated datasets, assess drought risk under changing climate using SPEI, and analyse future water availability based on projected hydrological changes. By integrating these components, the study seeks to provide a comprehensive understanding of the impacts of climate change on basin-scale water resources.

## 2.0. LITERATURE REVIEW

Hydrological extremes have been widely investigated in recent decades due to their increasing frequency and significant impacts on water resources, agriculture, and ecosystems. Climate change significantly influences the behaviour of these extremes by altering precipitation patterns and temperature regimes. Studies have shown that the intensification of the hydrological cycle has led to increased variability in runoff and soil moisture conditions, particularly in semi-arid regions (Shah & Mishra, 2020; IPCC, 2021). In India, the variability of the monsoon system plays a dominant role in shaping hydrological extremes, with strong linkages to large-scale climate drivers such as ENSO.

Researchers have progressed from basic statistical analyses to more advanced approaches that incorporate probabilistic methods and run theory to characterize hydrological extremes. Run theory, introduced by Yevjevich (1967), provides a systematic framework for identifying drought events and quantifying their characteristics, including severity, duration, and frequency. Recent studies continue to use this framework for analysing long-term drought variability and understanding the temporal dynamics of extreme events. For example, long-term analyses in semi-arid regions of India using SPI have revealed significant variability in drought occurrence, with multiple severe and extreme drought years observed over extended periods (Sharma and Goyal, 2020). Drought indices remain central to the assessment of hydrological extremes. Researchers have extensively applied the Standardized Precipitation Index (SPI) across various climatic settings because it captures precipitation anomalies at multiple time scales. However, its limitation in neglecting temperature effects has led to the development of more comprehensive indices. The Standardized Precipitation Evapotranspiration Index (SPEI) has gained widespread acceptance as it incorporates both precipitation and potential evapotranspiration, making it particularly relevant under climate change conditions. Comparative studies have shown strong correlations between SPI and SPEI while also highlighting the enhanced capability of SPEI to detect prolonged and temperature-driven drought events (e.g. Gurrapu et al., 2014).

Recent work on drought assessment has increasingly leaned toward the Standardized Precipitation Evapotranspiration Index (SPEI) as a more reliable way to

capture the full picture of drought conditions. Unlike precipitation-based indices, SPEI accounts for both rainfall deficits and atmospheric demand through evapotranspiration, which makes it especially relevant in semi-arid regions where temperature plays a critical role (Gurrapu et al., 2014; Mwinjuma et al., 2026). As a result, it has proven effective in identifying not just the occurrence, but also the intensity and persistence of droughts under changing climate conditions (Gebrechorkos et al., 2025; Mwinjuma et al., 2026). Another important area of research focuses on understanding how drought evolves across the hydrological cycle. Studies using SPEI show that meteorological droughts do not immediately translate into hydrological droughts. Instead, hydrological deficits often lag behind due to delays in soil moisture depletion and groundwater storage (Zhu et al., 2021; Das et al., 2022). This propagation from rainfall deficits (captured by SPEI) into streamflow or groundwater drought can take months and is controlled by basin characteristics, land use, and subsurface storage (Zhu et al., 2021; Das et al., 2022). Rising temperatures complicate this process further by increasing evapotranspiration, which can intensify and prolong drought conditions as soils dry out faster (Das et al., 2022; Gebrechorkos et al., 2025).

The impacts of climate change on hydrology have also been extensively explored using climate model projections and hydrological simulations. Researchers use future climate outputs from GCMs and/or RCMs to compute indices like SPEI under different scenarios (Mohammadi et al., 2024; Gebrechorkos et al., 2025). These studies consistently indicate that rising temperatures will increase atmospheric evaporative demand and reduce effective precipitation, leading to more frequent and severe droughts (Mohammadi et al., 2024). In semi-arid basins, even modest warming can significantly exacerbate water security. Moreover, compound events such as simultaneous droughts and heatwaves further amplify water stress (Das et al., 2022; Mohammadi et al., 2024). To assess future water availability, researchers often link projections with hydrological models. Models such as the Variable Infiltration Capacity model (VIC) are widely used to simulate basin-scale processes, including streamflow, evapotranspiration, and groundwater recharge under changed climates. For example, Ali et al., (2018) reproduced historical and projected reservoir flows in several basins of India using a calibrated VIC hydrological model and downscaled CMIP5 GCM outputs. When combined with SPEI-based drought analysis, these models show that

climate change is likely to decrease dry season streamflow and increase flow variability. One study found that significant warming (~6 °C) would reduce summer flows even if total precipitation rises (Ali et al., 2018; Mohammadi et al., 2024). Overall, increased evaporative demand tends to reduce runoff and drying soil moisture, posing challenges for water management.

Despite these advances, notable gaps remain for basins like the Pennar. Few studies integrate long-term drought records, multi-index assessment (meteorological, hydrological, groundwater), and future climate projections within a unified framework. Many analyses rely on a single drought index or omit the changing climate's effect on hydrological response. Addressing these gaps requires a comprehensive approach that combines robust climate data, SPEI-based drought assessment, and physically based hydrological modelling (Das et al., 2022; Mwinjuma et al., 2026). In summary, the literature highlights the importance of SPEI as a unified drought metric that accounts for both precipitation and evapotranspiration (Gurrapu et al., 2014; Mwinjuma et al., 2026). By reflecting the supply – demand balance of water, SPEI captures drought severity and persistence more fully, especially in water-limited regions. Integrating SPEI analyses with climate projections and basin-scale hydrological modelling is essential to assess drought risks and future water availability. The present study builds on these advances by focusing on the Pennar River Basin and employing an SPEI-based framework to evaluate hydrological extremes under changing climate.

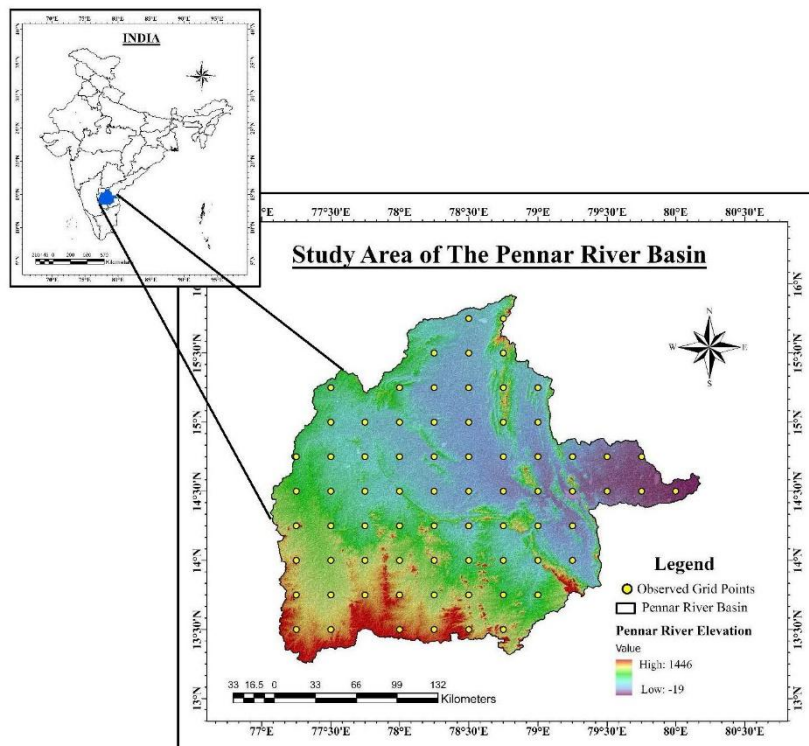
### **3.0. OBJECTIVES AND SCOPE OF STUDY**

To understand how hydrological extremes and water availability are changing in the Pennar River Basin, this study looks at both past conditions and possible future changes under a changing climate. By using observed data along with model-based simulations, the study aims to build a clearer picture of extreme events, drought behaviour, and their implications for water resources in the basin. The specific objectives of the study are as follows

1. Evaluate historical hydrological extremes in the Pennar River Basin using observed records and model simulated hydrological scenarios, and assess their characteristics (severity, duration, and frequency)
2. Assess drought risk under changing climate using several drought indices.
3. Assess future water availability in the basin based on the projected changes in basin hydrology.

#### 4.0. STUDY AREA & DATA USED

Pennar River basin located in the Peninsular India extends over the states of Andhra Pradesh ( $\approx 48,276 \text{ km}^2$ ) and Karnataka ( $\approx 6,937 \text{ km}^2$ ) with a total basin area of approximately  $55,213 \text{ km}^2$ , Figure 1. The basin lies between  $13^\circ 18'$  to  $15^\circ 49'$  N latitudes and  $77^\circ 1'$  to  $80^\circ 10'$  E longitudes. The river rises from the Chenna Kesava hills of the Nandi Ranges in Karnataka and flows about 597 km before draining in to the Bay of Bengal. The basin lies mostly in the rain shadow region of the Eastern Ghats, receives low rainfall, and frequently experiences drought. The annual mean rainfall received in the basin ranges between 400 mm (near Rayalaseema region) and 1200 mm (near coastal plains). The Indian Meteorological Department (IMD) operates and maintains various meteorological stations to monitor climatic conditions in the basin. This study used IMD gridded datasets to represent historical climate (precipitation at  $0.25^\circ$  spatial resolution and temperature at  $1^\circ$  spatial resolution).



**Figure 4.1.** Location of the Pennar River basin along with the selected grid of Precipitation and Temperature datasets from the available IMD gridded datasets of observed climate.

The study uses projected climate data from five Global Climate Models (GCM), selected from a set of 36 CMIP6 models, to assess changes in drought characteristics under a changing climate. Various research institutes and centres across the world develop these GCMs at different spatial resolution and run them using different initial and boundary conditions. Table 1 lists the vital information of the selected GCMs. Raw output from these five GCMs are bias corrected and downscaled to a common grid of 0.25° resolution by NASA Center for Climate Simulation. NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6) data set is comprised of global downscaled climate scenarios derived from the GCM runs conducted under the CMIP6 and across two of the four “Tier 1” greenhouse gas emissions scenarios known as Shared Socioeconomic Pathways (SSP). This dataset provides global, high resolution, bias-corrected climate change projections to evaluate impacts on processes that are sensitive to finer-scale climate gradients and local topographic effects. NASA adopts a statistical downscaling algorithm, Bias-Correction Spatial Disaggregation (BCSD) method for bias correct the CMIP6 GCM output. The climatic variables used of this study are mean (*tas*), maximum (*tasmax*), and minimum (*tasmin*) temperature in °K and mean daily precipitation rate (*pr*) in kg/m<sup>2</sup>/sec.

**Table 4.1.** List of selected CMIP6 Global Climate Models (GCMs) used in the study.

| CMIP6 GCM     | Institute   |
|---------------|---|
| BCC-CSM2-MR   | Beijing Climate Centre                            |
| ACCESS-ESM1-5 | CSIRO   |
| INM-CM4-8     | Institute for Numerical Mathematics (INM), Russia |
| CanESM5       | Canadian Center for Climate Modeling and Analysis |
| EC-Earth3     | EC-EARTH Consortium, The Netherlands/Ireland      |

To evaluate water availability in the Pennar River Basin under changing climate conditions, this study will build on the hydrological projections generated using the calibrated VIC model developed in an earlier project titled “*Climate Change Scenarios for Andhra Pradesh and its Impact on Streamflow and Groundwater levels in the Pennar River Basin*”. That work established a reliable modelling framework for simulating basin-scale hydrological responses under different climate scenarios. In the present study, we use these projections to examine changes in basin-averaged water availability.

## 5.0. METHODOLOGY

This study uses a comprehensive methodological framework to evaluate historical drought characteristics and to develop probabilistic projections of drought severity in the Pennar River Basin under changing climatic conditions. It centres on the Standardized Precipitation Evapotranspiration Index (SPEI) combined with the Drought Severity-Duration-Frequency (SDF) curves derived using the Generalized Extreme Value (GEV) distribution. This integrated approach captures drought processes more realistically by accounting for both precipitation deficits and atmospheric water demand, while also allowing probabilistic assessment of drought risk across different durations and severities.

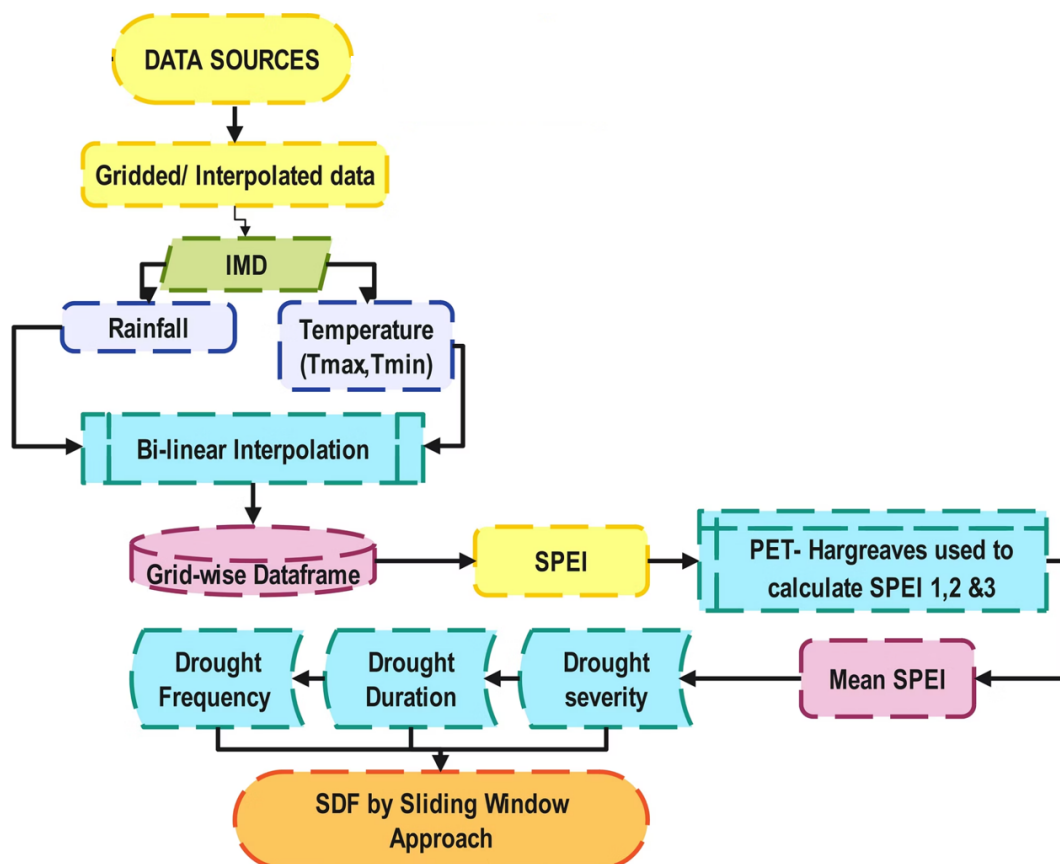
### 5.1. Standardised Precipitation Evapotranspiration Index (SPEI)

We used historical monthly precipitation and temperature data for the Pennar River Basin obtained from the India Meteorological Department (IMD). The precipitation data have a spatial resolution of  $0.25^\circ$ , while temperature data are available at  $1^\circ$ , covering the period 1951–2022. We carried out standard quality control, including consistency checks, outlier detection, and gap filling where needed. Because the datasets came at different spatial resolutions, we re-gridded the temperature data to the  $0.25^\circ$  precipitation grid using bilinear interpolation to maintain spatial consistency in the analysis. We calculated the SPEI using the climatic water balance, defined as the difference between precipitation and potential evapotranspiration (PET). We estimated PET using the Thornthwaite method, which works well for the regional studies with limited meteorological inputs. We then aggregated the monthly water balance series at 3-, 6-, and 12-month timescales to represent short-, medium-, and long-term drought conditions. Next, we fitted these aggregated series to a log-logistic probability distribution and transformed into standardized values to generate the SPEI time series. By accounting for both precipitation deficits and atmospheric evaporative demand, SPEI provides a more physically meaningful representation of drought, particularly under warming climate conditions.

### 5.2. Historical Drought Assessment

We identified drought events from the SPEI time series using a threshold-based approach. We marked the start of a drought when the SPEI dropped to or below  $-1.0$

and considered it over once it rose above this threshold. For each event, we extracted three key characteristics: (i) duration, the number of consecutive months with SPEI below the threshold; (ii) severity, the cumulative sum of negative SPEI values during the event; and (iii) intensity, calculated as the ratio of severity to duration. This process helped us build a comprehensive catalogue of historical drought events across the basin. To examine the probabilistic behaviour of droughts, we constructed Drought Severity–Duration–Frequency (SDF) curves. We grouped drought events by duration (e.g., 3-, 6-, and 12-month events) and used the corresponding severity values to fit the Generalized Extreme Value (GEV) distribution. The GEV distribution, widely used in extreme value analysis, can capture different types of tail behaviour through its shape parameter. We estimated the model parameters using the maximum likelihood estimation (MLE) method, and assessed the goodness-of-fit with standard statistical tests, including the Kolmogorov–Smirnov and Anderson–Darling tests, to ensure robust results.



**Figure 5.1.** Workflow for drought characterisation in the Pennar River Basin, illustrating the processing of IMD gridded rainfall and temperature data, interpolation and grid preparation, computation of SPEI (1-, 3-, 6-month).

We used the fitted GEV distribution to estimate the return periods of identified drought events and to derive the corresponding severity values for each event. We then used these estimates to develop SDF curves, which describe the probabilistic relationship between drought severity, duration, and frequency of occurrence. We constructed these curves for multiple drought durations to capture drought risk across different temporal scales within the basin. This approach provides a clearer understanding of how drought characteristics change with increasing duration and rarity. To examine temporal variability and possible non-stationarity in drought behaviour, we applied a sliding window approach over the historical period from 1951 – 2020. We evaluated SDF relationships separately for overlapping climatic windows: 1951-1980, 1961-1990, 1971-2000, 1981-2010, and 1991-2020. This allowed us to track changes in drought severity and frequency under evolving climatic conditions and to identify emerging trends in extreme drought characteristics. Figure 5.1 presents a schematic overview of the entire methodological framework, including data pre-processing, drought identification, extreme value analysis, and SDF curve development.

### **5.3. Impact of Climate Change**

We assessed the potential impacts of climate change on drought characteristics using bias-corrected outputs from selected GCMs under two SSPs, viz. SSP245 and SSP370, representing a range of future emission scenarios. Bias correction helps reduce systematic errors in raw climate model outputs and improves the reliability of projected hydro-climatic variables. We used future projections of precipitation and temperature to recompute the SPEI, ensuring a consistent assessment of drought conditions under changing climatic regimes. We carried out the analysis for two future periods: mid-century (2041-2070) and late-century (2071-2100), capturing both near-term and long-term climate change signals. We then applied the same methodological framework used for the historical analysis to projected datasets. We identified drought events from the SPEI time series and extracted their key characteristics – duration, severity, and frequency. Using these, we updated the SDF curves for each future scenario. This approach allows direct comparison between historical and projected drought behaviour and helps evaluate how drought frequency, intensity and persistence may evolve under different climate pathways.

Overall, this integrated framework combines SPEI-based drought characterisation, extreme value analysis, and climate model projections to provide a consistent and robust assessment of drought risk in the Pennar River Basin under both present and future conditions. By capturing the probabilistic nature of extreme drought events and their potential shifts due to climate change, the approach offers practical insights for water resource planning, reservoir operation, and long-term policy decisions. It also supports the development of climate-resilient drought mitigation and adaptation strategies, especially in semi-arid regions where water availability remains highly sensitive to climate variability.

#### **5.4. Assessment of Water Availability**

We assessed the impacts of climate change on water availability in the Pennar River Basin using a modelling framework based on Variable Infiltration Capacity (VIC) hydrological model. We built this analysis on an already developed and calibrated VIC setup from the project titled "*Climate change scenarios for Andhra Pradesh and its Impact on Streamflow and Groundwater levels in Pennar River Basin*". Using a calibrated and validated hydrological model helped us represent basin-scale hydrological processes more reliably and reduced uncertainties related to model structure and parameters. The VIC model captures key components of the water balance such as surface runoff, baseflow, evapotranspiration, and soil moisture. We used future climate projections from an ensemble of five carefully selected GCMs and we carried out this analysis for two-time periods: mid-century (2041-2070) and late-century (2071-2100), which capture both intermediate and long-term climate change impacts, Figure 5.2.

We ran the VIC model simulate water balance components under both historical and future climate conditions. We directly used the existing calibrated setup without making structural changes. We forced the model with bias-corrected climate projections at a daily time step, which improved the reliability of simulations by reducing systematic errors in raw GCM outputs. For each GCM and SSP combination, we generated continuous time series of key variables such as runoff, evapotranspiration, soil moisture and baseflow. We assessed water availability primarily through simulated runoff and baseflow, which represents the total water yield from the land surface system. We used a historical baseline period (1981-2010) as a

reference to quantify changes under future climate scenarios. The analysis focused on both the magnitude and temporal variability of runoff to understand how water availability may evolve under changing climatic conditions. We examined changes in mean annual and seasonal runoff to identify shifts in overall water yield and intra-annual distribution. We also analysed variations in baseflow to evaluate changes in subsurface water availability and potential impacts on groundwater recharge. In addition, we assessed evapotranspiration and soil moisture to understand how changes in precipitation and atmospheric demand influence water partitioning within the basin.

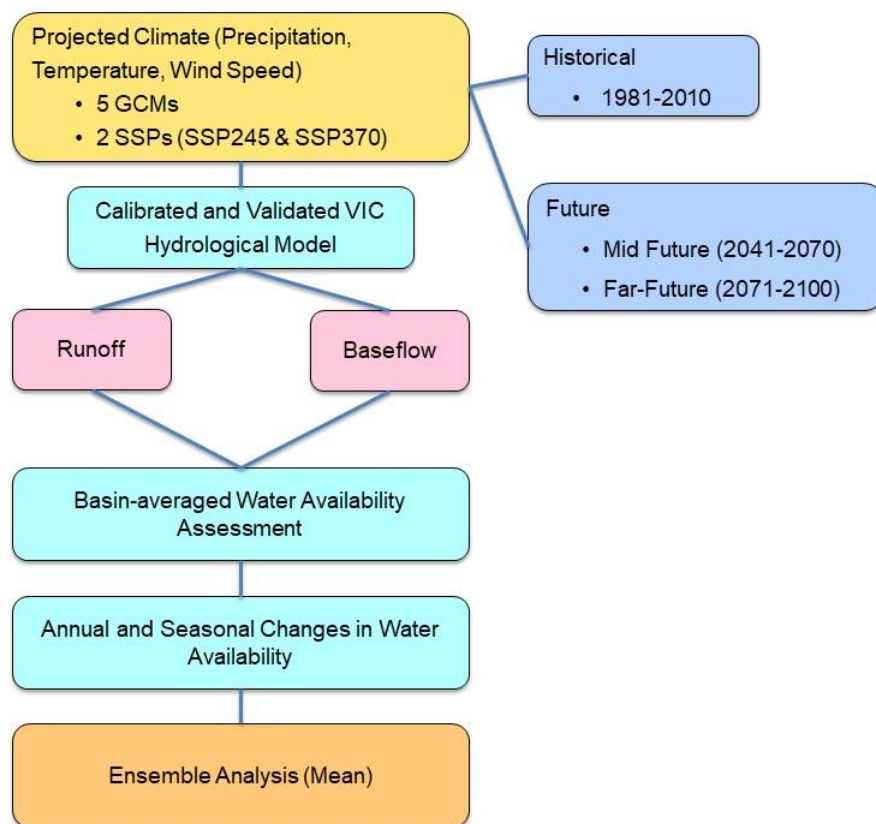


Figure 5.2. Methodological framework for assessing water availability in the Pennar River Basin using a calibrated VIC hydrological model, driven by multi-GCM climate projections under SSP245 and SSP370 scenarios, comparing historical (1981-2010) and future (mid- and far-century) periods.

We compared the baseline and future periods to identify systematic changes in hydrological behaviour. This helped us detect shifts in seasonal water availability, changes in runoff variability, and possible alterations in hydrological extremes such as

prolonged dry conditions. To address uncertainties in climate projects, we adopted an ensemble approach and analysed simulations from all five selected GCMs together. We used ensemble statistics – such as mean response, range, and inter-model variability – to develop a probabilistic understanding of future water availability and to identify consistent trends across models. Finally, we interpreted the projected changes in runoff and related hydrological variables in the context of water resources management within the basin. By focusing on runoff as a direct indicator of water availability and combining climate projections with a physically based hydrological model, this approach provides a consistent and robust framework for assessing the impacts of climate change on basin-scale water resources.

## 6.0. RESULTS AND DISCUSSION

### 6.1. Historical Drought Assessment

The first objective is to evaluate the historical droughts in the Pennar River Basin and assess their characteristics, viz. severity, duration and frequency. Figure 6.1 shows how drought conditions have varied over time across the Pennar River Basin using SPEI at three different timescales, viz. SPEI-1, SPEI-3, SPEI-6, all derived from IMD gridded data. Each panel reflects a different level of moisture accumulations, where red bars indicate drought conditions, blue bars represent wet periods, and orange bars show near-normal conditions. At the monthly scale (SPEI-1), the series fluctuate rapidly, with frequent shifts between wet and dry phases. This highlights how short-term climate variability drives quick changes in moisture availability across the basin. At a 3-month and 6-month timescales, the patterns become much clearer and more meaningful from a hydrological perspective. The SPEI-3 series begins to smooth out these short-term fluctuations and reveals seasonal drought signals, where dry periods last longer and show more continuity. By the time we look at SPEI-6, the drought events appear even more persistent and intense, capturing the cumulative effect of prolonged moisture deficits. These longer-duration droughts reflect conditions that influence streamflow, groundwater, and overall water availability.

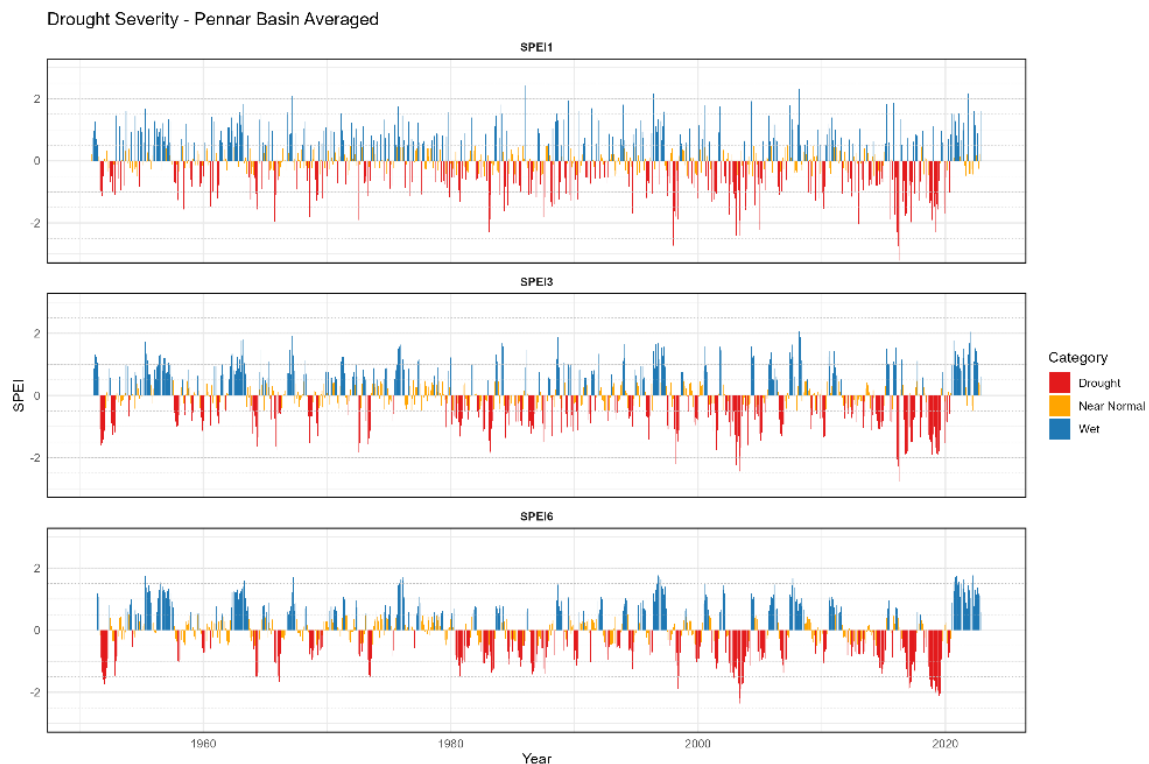


Figure 6.1. Temporal variation of basin-averaged drought severity over the Pennar River Basin derived from IMD gridded data using the Standardized Precipitation Evapotranspiration Index (SPEI) at three time scales: SPEI-1 (1-month), SPEI-3 (3-month), and SPEI6 (6-month). Negative values (red) indicate drought, positive values (blue) represent wet, and orange shows near-normal conditions.

Several notable dry periods stand out across all three scales, particularly during the late 1990s, early 2000s, and again in the late 2010s. These periods show strong and sustained negative SPEI values, especially in the SPEI-6 panel, indicating severe and prolonged drought conditions across the basin. In contrast, earlier decades display relatively balanced conditions with alternating wet and dry phases and fewer extended drought episodes. Figure 6.1 clearly shows that while short-term variability dominates at the monthly time scale, longer time scales reveal the true extent and persistence of droughts in the Pennar basin. As we move from SPEI-1 to SPEI-6, we can clearly see how short-term rainfall deficits build up over time and turns into more serious hydrological droughts, placing increasing stress on water resources and overall basin sustainability.

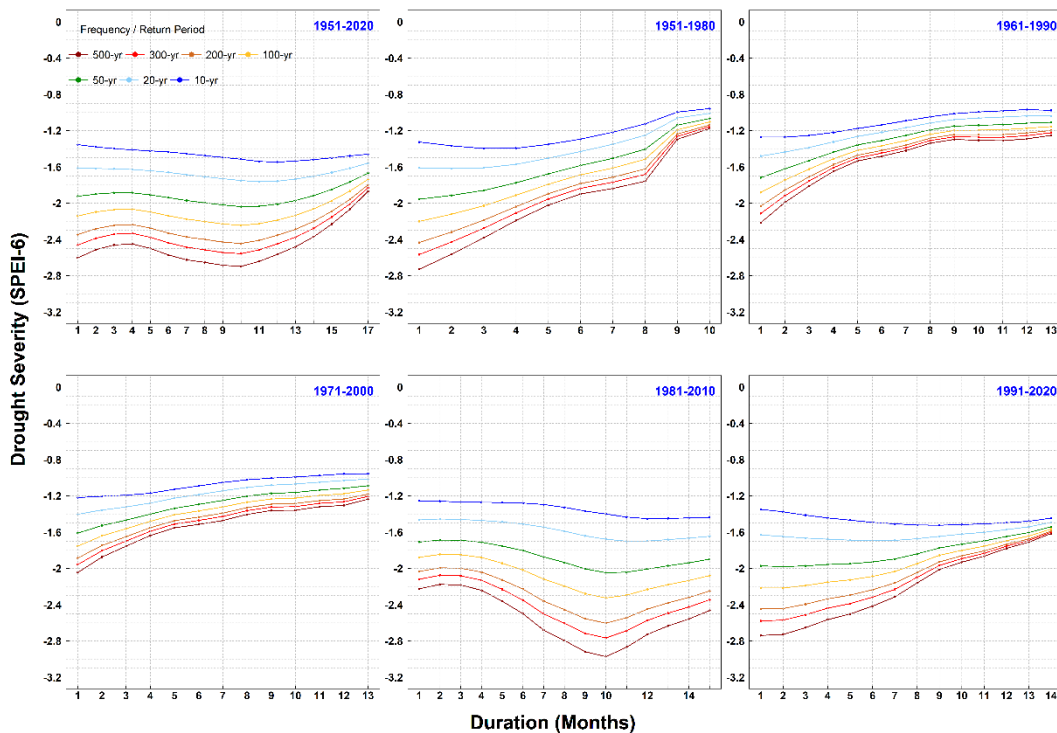


Figure 6.2. Severity-Duration-Frequency (SDF) curves based on the SPEI-6 index for the Pennar River Basin, illustrating drought severity as a function of duration for the

full study period (1951-2020) and five overlapping 30-year climatic windows (1951-1980, 1961-1990, 1971-2000, 1981-2010, and 1991-2020).

Figure 6.2 shows the Severity-Duration-Frequency (SDF) curves based on the SPEI-6 index. The figure shows a clear and meaningful picture of how drought behaviour has changed across the Pennar River Basin from 191 to 2020. By using a sliding window approach, we move beyond a single long-term perspective and instead compare the full-period SDF relationship with five overlapping climatic windows (1951-1980, 1961-1990, 1971-2000, 1981-2010, and 1991-2020). This approach allows us to track how drought characteristics shift over time and to examine whether the basin still follows the assumption of stationarity, which often underpins traditional frequency analysis. A consistent pattern emerges across all time windows: drought severity increases steadily with duration. This makes intuitive sense, as longer drought events allow moisture deficits to accumulate over time. However, when we look more closely at how the curves position themselves across different periods, important differences begin to appear. The earlier windows, particularly 1951-1980 and 1961-1990, show relatively lower severity for a given duration. These periods reflect more moderate long-term drought conditions, where even extended dry spells did not intensify as sharply.

As we move toward recent decades, the behaviour changes noticeably. The curves for 1981-2010 and especially 1991-2020 shift upward across almost all durations. This means that for the same drought duration, the basin now experiences greater severity than it did in the past. The difference becomes even more striking at longer durations, where the curves separate more clearly. This pattern suggests that prolonged droughts have not only become more frequent but also more intense, pointing to a strengthening of hydrological stress in the basin over time. The spread between curves across different windows tells an important story. Instead of collapsing onto a single relationship, the curves diverge, indicating that drought characteristics have not remained constant. This temporal variability raises a serious question about the validity of assuming stationarity in drought analysis for this region. In practical terms, it means that the past no longer serves as a reliable guide to the future, especially when it comes to long-duration drought events.

The steeper and higher curves in recent periods also highlight the nature of SPEI-6 itself. Since this index captures medium-term moisture conditions, it reflects the cumulative impact of rainfall deficits, evapotranspiration, and soil moisture depletion. As a result, the observed intensification directly connects to processes that control streamflow, groundwater recharge, and overall water availability. Taken together, the SDF analysis clearly shows that droughts in the Pennar River basin have become more severe over time, particularly for longer durations that matter most for water management. This evolving behaviour highlights the importance of incorporating non-stationarity into drought risk assessments and planning strategies. If we continue to rely only on historical averages or stationary assumptions, we risk underestimating the likelihood and impact of future prolonged droughts, which could have serious implications for agriculture, water supply, and basin-scale water availability.

## **6.2. Future Drought Assessment**

The SDF curves based on SPEI-1, shown in Figure 6.3, highlight how short-term drought characteristics evolve across the Pennar River Basin under historical and future climate conditions, as represented by the five GCMs. For the historical baseline period (1981-2010), all models show a consistent relationship where drought severity increases with duration and return period. Higher return period events (e.g., 100-500 years) exhibit substantially greater severity compared to more frequency events, while shorter durations (1-2 months) capture sharper and more intense fluctuations typical of meteorological droughts. When we move into the mid-century period (2041-2070), noticeable shifts begin to emerge across most models. Several GCMs, including ACCESS-ESM1-5 and CanESM5, show an upward shift in the SDF curves, indicating an increase in drought severity for the same duration and return period. This change becomes particularly evident for higher return period events, suggesting that extremes short-term droughts intensify under projected climate conditions. However, not all models respond uniformly, for example BC-CSM2-MR and INM-CM4-8 display relatively moderate changes, with some durations showing only marginal increases or near-stable behaviour.

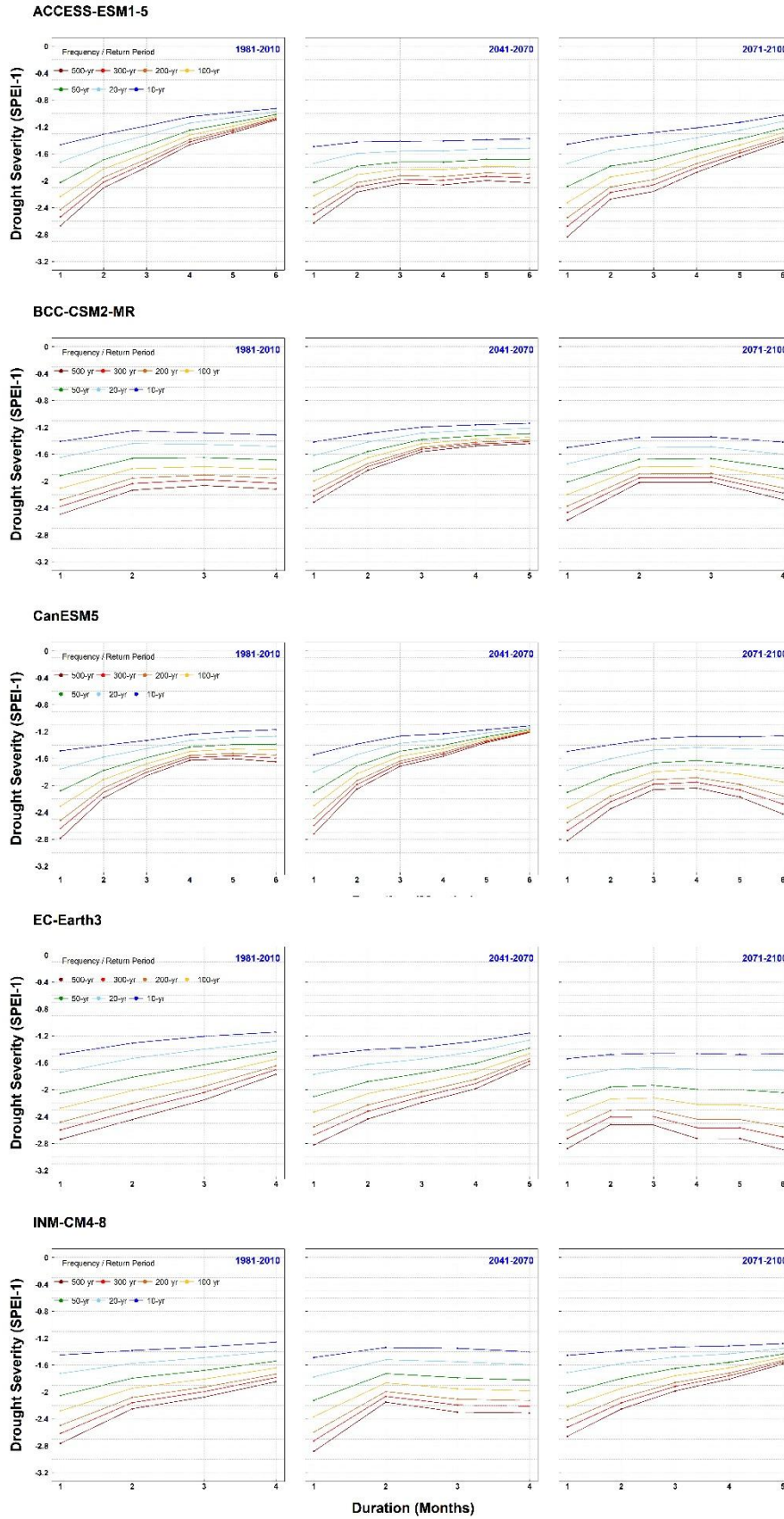


Figure 6.3. Severity-Duration-Frequency (SDF) curves based on the SPEI-1 index for the Pennar River Basin, derived from five GCMs (ACCESS-ESM1-5, BCC-CSM2-MR,

CanESM5, EC-Earth3, and INM-CM1-8) for the historical baseline period (1981-2010) and two future periods: mid-century (2041-2070) and late-century (2071-2100) under SSP245 scenario.

The late-century period (2071-2100) strengthens these patterns, although model-specific differences remain important. ACCESS-ESM1-5 and INM-CM4-8 continue to show a clear increase in severity across most durations, pointing toward a consistent intensification of short-term droughts. CanESM5 and EC-Earth3, on the other hand, show more complex behaviour, where severity increases at shorter durations but tends to stabilise or slightly reduce at longer durations. This suggests that while short bursts of drought may become more intense, their persistence at the monthly scale does not always increase proportionately across all models. Across all GCMs, the spread between curves representing different return periods remains distinct in both historical and future scenarios, indicating that the frequency-severity relationship continues to hold under changing climate conditions. However, the shifting position of these curves, particularly in the mid- and late-century periods, points to a gradual intensification of meteorological drought risk in the basin. Overall, the SPEI-1 based SDF analysis suggests that short-term droughts in the Pennar River Basin are likely to become more severe in the future, especially for less frequent but high-impact events. At the same time, the variation across GCMs highlights the role of model uncertainty, reinforcing the need to interpret future projections as a range of plausible outcomes rather than a single deterministic trend.

As we move to SPEI-3, the behaviour becomes more structured and easier to interpret Figure S3. The curves smooth out, and the relationship between duration and severity becomes more consistent across all models. Compared to SPEI-1, the separation between different return periods looks more stable, which suggests that seasonal droughts follow a more predictable pattern. In the future periods, most models show a clear upward shift in these curves, particularly for moderate to longer durations. This indicates that seasonal droughts are likely to intensify more steadily than short-term events. At the SPEI-6 scale, the patterns become even more coherent, Figure S4. The curves rise smoothly with duration, and the spacing between return periods remains uniform across models. At this scale, droughts reflect accumulated moisture deficits, so they capture longer-term stress on the system. The future projections show a stronger and more consistent increase in severity here than at

shorter time scales. In particular, longer-duration events stand out, with most models indicating deeper and more persistent drought conditions. Looking at all the timescales together, the shift is quite clear. SPEI-1 highlights variability and model differences, but SPEI-3 and SPEI-6 reveal a much stronger and more consistent signal of change. As the accumulation period increases, the noise reduces and the underlying trend becomes more visible. This suggests that future climate change will not just influence short-term rainfall variability, but will also strengthen longer and more impactful droughts that directly affect water availability and basin-scale hydrology.

Table 6.1. Change in drought severity at 50-year return period for a 3-month duration across different GCMs under the SSP245 scenario, comparing mid-century (2041-2071) conditions with the historical baseline (1981-2010). The table presents SPEI-based estimates at multiple time scales (SPEI-1, SPEI-3, and SPEI-6), along with the corresponding absolute and percentage change in drought severity.

| GCM           | SPEI  | Drought Severity        |                        | Delta Change | Percentage Change |
|---------------|-------|-------------------------|------------------------|--------------|-------------------|
|               |       | Mid-Century (2041-2070) | Historical (1981-2010) |              |                   |
| ACCESS-ESM1-5 | SPEI1 | -1.93335                | -1.47656               | -0.45679     | -30.9359          |
| BCC-CSM2-MR   | SPEI1 | -1.74784                | -1.64857               | -0.09927     | -6.02134          |
| CanESM5       | SPEI1 | -1.55718                | -1.5874                | 0.030218     | 1.903598          |
| EC-Earth3     | SPEI1 | -1.80791                | -1.62877               | -0.17914     | -10.9985          |
| INM-CM4-8     | SPEI1 | -1.8239                 | -1.67841               | -0.14549     | -8.66818          |
| ACCESS-ESM1-5 | SPEI3 | -1.92024                | -1.60813               | -0.31211     | -19.4083          |
| BCC-CSM2-MR   | SPEI3 | -1.84408                | -1.65012               | -0.19396     | -11.7546          |
| CanESM5       | SPEI3 | -1.84431                | -1.77417               | -0.07014     | -3.95355          |
| EC-Earth3     | SPEI3 | -1.88978                | -1.66125               | -0.22854     | -13.7568          |
| INM-CM4-8     | SPEI3 | -1.94487                | -1.77407               | -0.1708      | -9.62734          |
| ACCESS-ESM1-5 | SPEI6 | -1.83387                | -1.78576               | -0.04811     | -2.69381          |
| BCC-CSM2-MR   | SPEI6 | -2.0457                 | -1.66879               | -0.37691     | -22.5859          |
| CanESM5       | SPEI6 | -1.80424                | -1.81817               | 0.013928     | 0.766068          |
| EC-Earth3     | SPEI6 | -1.79017                | -1.67357               | -0.11659     | -6.96681          |
| INM-CM4-8     | SPEI6 | -1.94108                | -1.87593               | -0.06515     | -3.47277          |

Tables 6.1 and 6.2 summarises how drought severity of 3-month duration at a 50-year return period and is likely to change across the Pennar River Basin under the SSP245 scenario, comparing both mid-century (2041-2070) and late-century (2071-

2100) conditions with the historical baseline (1981-2010). Based on both the tables, a clear pattern begins to emerge, viz. droughts generally become more severe over time, although the extent of change varies across models and SPEI timescales. Starting with the mid-century period, most models already indicate a shift toward more severe drought conditions, particularly at the seasonal scale (SPEI-3). Models such as ACCESS-ESM1-5 and EC-Earth3 show changes. At the short-term scale (SPEI-1), the response remains mixed, with some models indicating intensification and others suggesting slight weakening. At the longer scale (SPEI-6), the behaviour becomes more variable across models, although a few models, especially BCC-CSM2-MR, point toward noticeable increases in drought severity.

Table 6.2. Change in drought severity at 50-year return period for a 3-month duration across different GCMs under the SSP245 scenario, comparing late-century (2071-2100) conditions with the historical baseline (1981-2010).

| GCM           | SPEI  | Drought Severity         |                        | Delta Change | Percentage Change |
|---------------|-------|--------------------------|------------------------|--------------|-------------------|
|               |       | Late-Century (2071-2100) | Historical (1981-2010) |              |                   |
| ACCESS-ESM1-5 | SPEI1 | -1.6977                  | -1.4766                | -0.2212      | -14.9779          |
| BCC-CSM2-MR   | SPEI1 | -1.6839                  | -1.6486                | -0.0354      | -2.1449           |
| CanESM5       | SPEI1 | -1.6749                  | -1.5874                | -0.0875      | -5.5121           |
| EC-Earth3     | SPEI1 | -1.7406                  | -1.6288                | -0.1118      | -6.8634           |
| INM-CM4-8     | SPEI1 | -1.5672                  | -1.6784                | 0.1112       | 6.6264            |
| ACCESS-ESM1-5 | SPEI3 | -2.0130                  | -1.6081                | -0.4048      | -25.1744          |
| BCC-CSM2-MR   | SPEI3 | -1.8610                  | -1.6501                | -0.2109      | -12.7813          |
| CanESM5       | SPEI3 | -1.9015                  | -1.7742                | -0.1273      | -7.1742           |
| EC-Earth3     | SPEI3 | -1.8831                  | -1.6612                | -0.2218      | -13.3530          |
| INM-CM4-8     | SPEI3 | -1.7721                  | -1.7741                | 0.0020       | 0.1123            |
| ACCESS-ESM1-5 | SPEI6 | -2.1698                  | -1.7858                | -0.3840      | -21.5027          |
| BCC-CSM2-MR   | SPEI6 | -2.0466                  | -1.6688                | -0.3778      | -22.6396          |
| CanESM5       | SPEI6 | -2.0171                  | -1.8182                | -0.1990      | -10.9433          |
| EC-Earth3     | SPEI6 | -1.8469                  | -1.6736                | -0.1734      | -10.3588          |
| INM-CM4-8     | SPEI6 | -1.7740                  | -1.8759                | 0.1019       | 5.4327            |

When we move further into the late-century, the signal becomes stronger and more consistent. Most models show a clear increase in drought severity across all three SPEI time scales, and the magnitude of change generally becomes larger than

in the mid-century. This trend stands out most clearly at the seasonal (SPEI-3) and medium-term (SPEI-6) scales. For instance, ACCESS-ESM1-5 shows substantial intensification of both SPEI-3 and SPEI-6, with percentage changes exceeding 20% in magnitude. BCC-CSM2-MR also indicates strong increases, particularly at SPEI-6, where the changes exceeds 22%. Even models that showed weaker signals in the mid-century, such as CanESM5, display clearer intensification by the late-century. However, not all models follow the same trajectory, INM-CM4-8, for example, shows a slight reduction or near-stable behaviour in some cases, even in the late-century. This highlights the role of model uncertainty and differences in how each GCM represents precipitation, temperature, and evapotranspiration processes. Overall, both the tables suggest that drought conditions intensify progressively from the mid-century to the late-century under the SSP245 scenario. The strengthening signal at SPEI-3 and SPEI-6 indicates that droughts lasting several months are likely to become more severe and persistent. This has important implications for water availability, agriculture, and basin-scale water management, as longer-duration droughts tend to place greater stress on surface and groundwater resources.

### **6.3. Impacts of Climate Change on Water Availability**

Figures 6.4 to 6.6 together provide a detailed picture of how basin-averaged runoff in the Pennar River Basin is likely to evolve under future climate conditions, considering both SSP245 and SSP370 scenarios. These figures highlight the changes in magnitude and redistribution of runoff across months and seasons. Figure 6.4 presents the basin-averaged monthly runoff (ensemble mean), and it clearly shows that the Pennar Basin continues to follow a strong monsoon-driven regime. Under historical conditions, runoff remains low from January to May, starts rising in June-July, and peaks sharply during the monsoon and early post-monsoon months (August to October). When we compare this with future projection, a clear intensification emerges. Under SSP245, runoff increases noticeably from the historical period to the mid- and late-century, especially during the monsoon and post-monsoon months. The late-century curve rises much higher during September and October, indicating strong peak flows. Under SSP370, the same pattern becomes much stronger. Runoff increases earlier in the season, peaks more sharply, and remains elevated for a longer duration. This shift suggests that the basin will experience stronger and more concentrated monsoon flows under higher emission scenarios.

### Monthly Basin Runoff (Ensemble Mean)

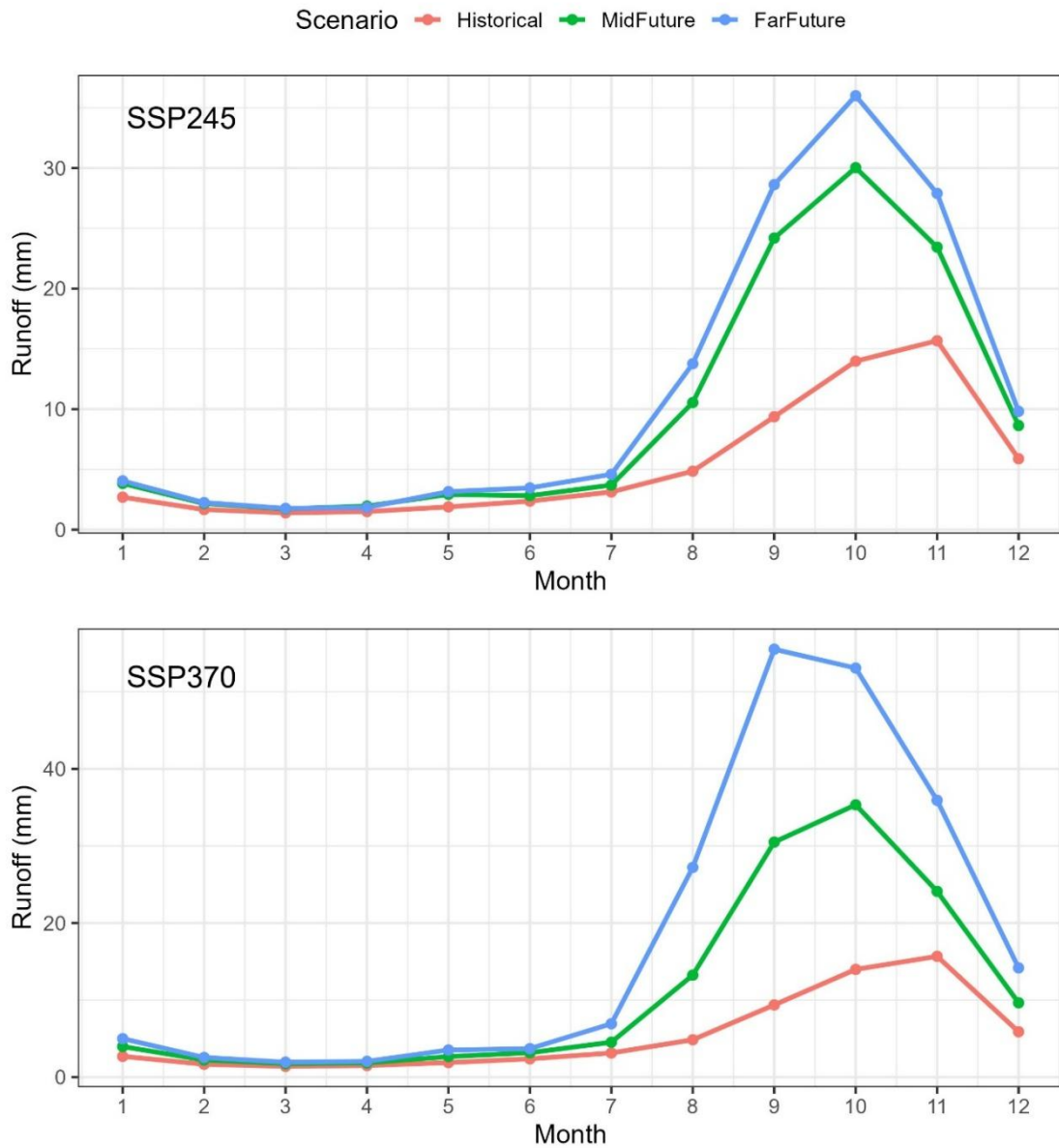


Figure 6.4. Basin-averaged monthly runoff (ensemble mean) for the Pennar River Basin under historical (1981-2014), mid-century (2041-2070), and late-century (2071-2100) periods for SSP245 (top) and SSP370 (bottom) scenarios, showing changes in the magnitude and seasonal distribution of runoff across the year.

Figure 6.5 translates these monthly patterns into seasonal contribution and helps us understand where these changes concentrate. The monsoon and post-monsoon seasons dominate the increase in runoff across both scenarios. Under SSP245, monsoon runoff increases substantially from historical to late-century conditions, but post-monsoon runoff shows an even larger jump, indicating a strengthening of late-season flows. Under SSP370, this pattern becomes more

pronounced, with post-monsoon runoff increasing dramatically in the late-century. In contrast, pre-monsoon and winter seasons show only modest increases in runoff. This imbalance highlights a critical shift: the basin gains more water during wet seasons, but dry-season water availability improves only slightly, which could continue to stress water resources outside the monsoon period.

### Seasonal Basin Runoff

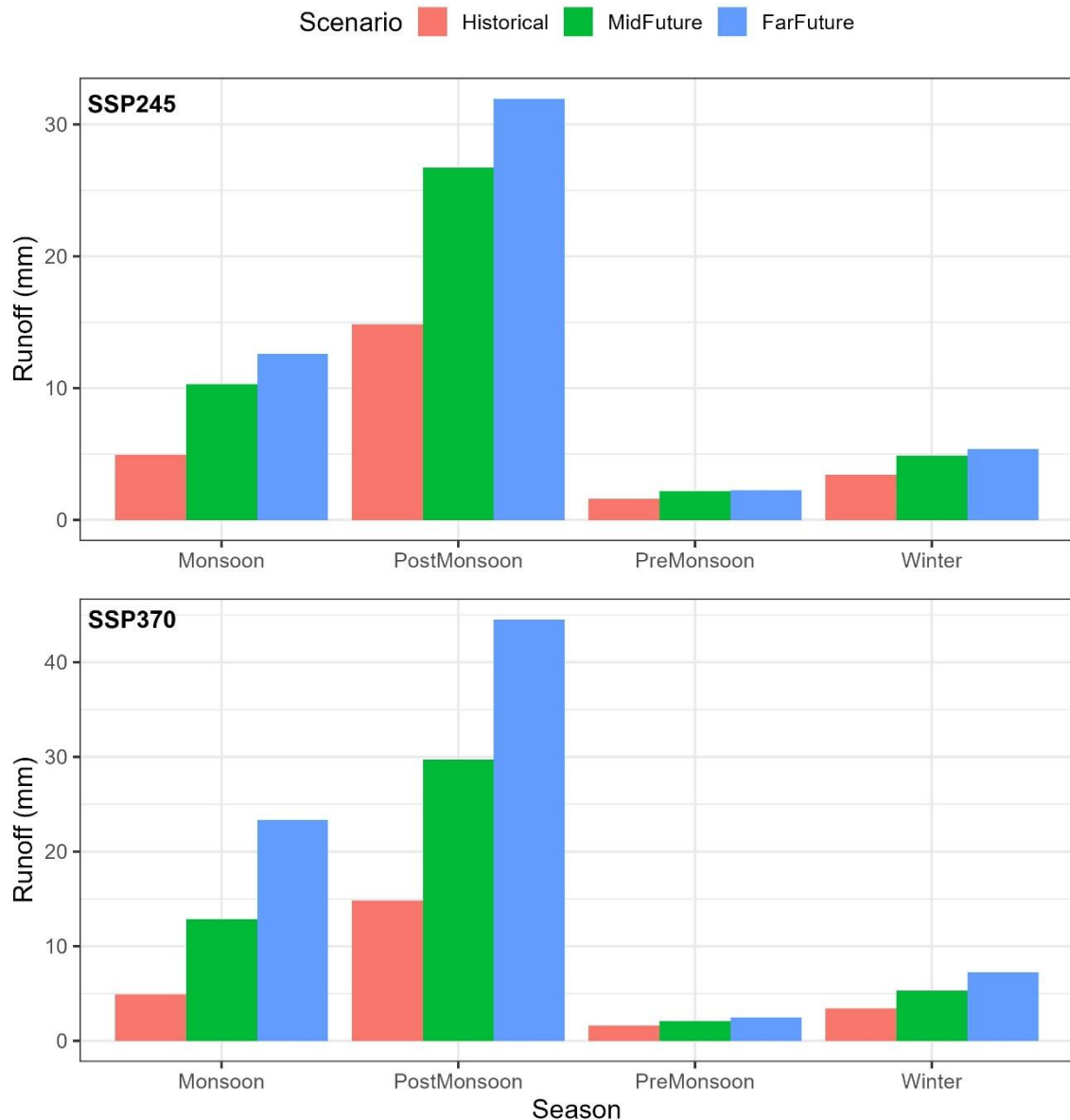


Figure 6.5. Seasonal basin-averaged runoff (ensemble mean) for the Pennar River Basin under historical (1981-2010), mid-century (2041-2070), and late-century (2071-2100) periods for SSP245 (top) and SSP370 (bottom) scenarios, highlighting shifts in runoff distribution across monsoon, post-monsoon, and pre-monsoon and winter seasons.

Figure 6.6 quantifies these changes in terms of percentage increase in runoff and makes the scale of change much clearer. Under SSP245, runoff increases across all months, but the largest increase occur during the monsoon peak, particularly between August and October. In the late-century, these increases exceed 150-200% for some months, showing a strong amplification of peak flows. Under SSP370, the magnitude of change becomes much larger, peak monsoon months (especially September) shows extremely high increases, reaching several hundred percent in the late-century. Even months like July and October exhibit substantial increases. These results indicate that higher emission scenarios not only increase runoff but also significantly amplify hydrological extremes.

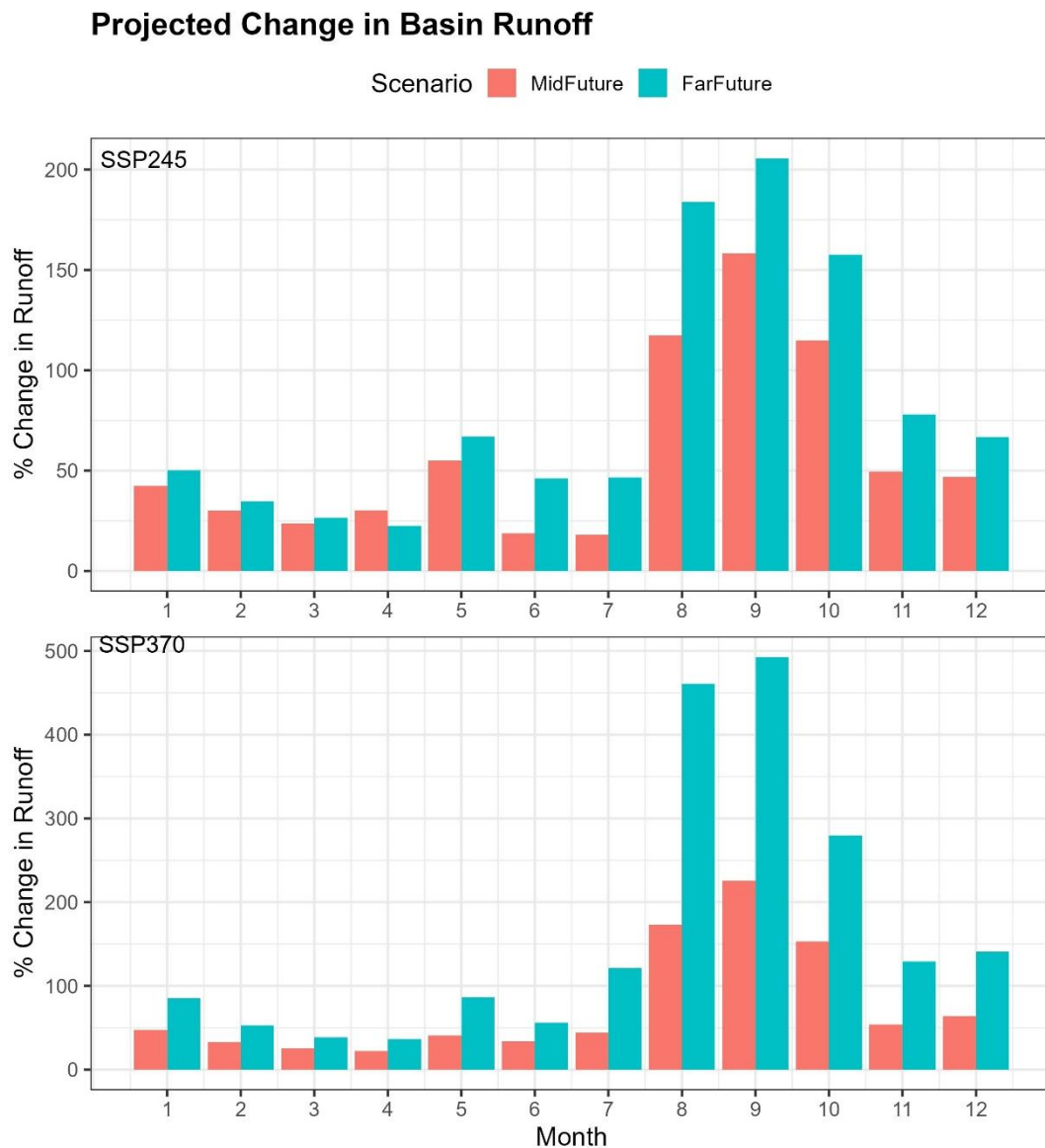


Figure 6.6. Projected percentage change in basin-averaged monthly runoff relative to the historical period (1981-2010) for mid-century (2041-2070) and late-century (2071-

2100) periods under SSP245 (top) and SSP370 (bottom) scenarios, illustrating the magnitude and seasonal variation of runoff charges across the Pennar River Basin

In summary, the Figures 6.4 to 6.6 show a consistent picture of water availability in the Pennar River Basin. Figure 6.4 shows how the timing and magnitude of runoff change through the year, Figure 6.5 highlights the seasonal redistribution of water, and Figure 6.6 quantifies how large these changes become. Together, they reveal that future climate conditions will not increase runoff uniformly. Instead, they will concentrate more water into the shorter and more intense monsoon period, particularly under SSP370. This leads to higher peak flows during the wet season, while dry-season runoff shows only limited improvement. Such a shift increases the risk of flooding during the monsoon and maintains pressure on water availability during the rest of the year, posing significant challenges for basin-scale water management in the Pennar River Basin.

## 7.0. SUMMARY AND CONCLUSIONS

This study examines how hydrological extremes and water availability in the Pennar River Basin are evolving under changing climatic conditions. By combining observed climate data, drought analysis using SPEI and hydrological simulations from the VIC model driven by multiple CMIP6 GCMs, the analysis builds a comprehensive understanding of how climate variability translates into drought behaviour and water availability at the basin scale. The historical assessment shows that drought characteristics in the Pennar Basin have changed noticeably over time. Short-term fluctuations dominate the monthly scale, but longer time scales reveal more persistent and hydrologically meaningful drought conditions. In recent decades, droughts have become more severe, particularly for longer durations. The SDF curves clearly reflect this shift, with recent times showing higher severity from the same duration compared to earlier decades. This change indicates that drought behaviour is no longer stationary, and the assumption that past conditions can reliably represent future risks does not hold true for this basin.

Future projections reinforce and extend these findings. Most of the selected GCMs indicate an increase in drought severity under both SSP245 and SSP370 scenarios. The signal becomes stronger and more consistent as we move from short-term droughts to seasonal and medium-term droughts represented by SPEI-3 and SPEI-6. Seasonal droughts, in particular, show a clear and systematic intensification across models. By the late-century period, the majority of models point toward deeper and more persistent drought conditions, especially for durations that directly influence water resources. Although some variability exists across models, the overall trend remains consistent and indicates increasing drought risk in the basin. At the same time, the hydrological simulations present a different but equally important perspective on water availability. The results show that runoff in the Pennar Basin is projected to increase in the future, particularly during the monsoon and post-monsoon seasons. The ensemble mean clearly highlights a rise in peak flows, with the most significant increases occurring between August and October. Under the higher emission scenario (SSP370), these increases become more pronounced, with sharper peaks and a longer duration of elevated flows. However, this increase in runoff does not occur uniformly throughout the year. The seasonal analysis reveals that most of the

additional water concentrates in the monsoon and post-monsoon periods, while the pre-monsoon and winter seasons experience only modest changes. This creates a clear imbalance in water availability, where wet-season flows increase substantially but dry-season conditions remain relatively constrained. The percentage change analysis further emphasizes this pattern, showing very large increases during peak monsoon months, particularly under SSP370, where some months experience several-fold increases in runoff compared to historical conditions.

When considered together, the drought and runoff analyses reveal a critical and somewhat contrasting behaviour of the basin under climate change. On one hand, droughts become more severe and persistent, especially at seasonal and medium-term scales. On the other hand, runoff increases significantly, but mainly during already wet periods. This indicates that the basin does not simply become wetter or drier; instead, it becomes more variable and extreme. Water availability increases during the monsoon, but this does not necessarily translate into improved water security during dry periods. This imbalance highlights a key challenge for water resource management in the Pennar River Basin. The system experiences higher inflows during a shorter and more intense monsoon period, while dry-season water availability improves only marginally. As a result, the basin faces a dual risk of increased flood potential during the wet season and sustained drought stress during the dry season. This combination of intensifying extremes makes the system more vulnerable and more difficult to manage using traditional approaches based on historical averages.

The differences between SSP245 and SSP370 further underline the role of future emission pathways in shaping hydrological outcomes. The higher emission scenario consistently shows stronger increases in both drought severity and runoff, indicating that climate change impacts become more severe as warming intensifies. This reinforces the importance of considering multiple scenarios in planning and highlights the potential benefits of mitigation efforts in reducing future risks. Overall, the study demonstrates that climate change will fundamentally alter the hydrological behaviour of the Pennar River Basin. Increasing drought severity, combined with more intense and concentrated runoff, points toward a future where variability and extremes dominate the water cycle. These changes have significant implications for water

availability, agriculture, and long-term basin sustainably. Managing water resources in such a system will require a shift from reliance on historical patterns to more adaptive and forward-looking strategies that can account for increasing uncertainty and variability.

## 8.0. WAY FORWARD

The findings of this study show that the Pennar River Basin will face a future shaped by stronger variability and more intense extremes rather than a simple increase or decrease in water availability. The basin will receive more water during the monsoon, but it will also experience more severe and persistent droughts. This mismatch between water supply and demand across seasons creates a clear need to rethink how water resources are managed. Water managers and planners need to move beyond relying only on historical records. The study shows that drought behaviour and runoff patterns are already changing, and they will continue to change in the future. Planning based only on past conditions will underestimate future risks. Instead, decision-making should actively include climate projections such as SSP245 and SSP370, so that strategies reflect realistic future conditions.

The basin also needs to make better use of the increased monsoon runoff. Future projections show that a large share of water will arrive during a short and intense period. If this water flows out of the basin without being stored, it will not help during dry months. Expanding storage through reservoirs, check dams, and local water harvesting structures can help capture this excess runoff. At the same time, strengthening groundwater recharge systems can store water below the surface and support flows during dry periods. Reservoir operations must also become more flexible. Fixed operating rules based on past conditions will not work well when inflows in both timing and magnitude. Managers should use real-time data and seasonal forecasts to guide reservoir releases and storage decisions. This approach can help reduce flood risks during peak flows while ensuring that enough water remains available for dry-season use.

Drought management needs to become more proactive. The study shows that droughts are likely to become more severe, especially over seasonal and longer time scales. Instead of reacting after drought conditions develop, managers should use early warning systems based on indices like SPI to anticipate stress. Linking these warnings with timely decisions, such as adjusting irrigation schedules or planning crop choices, can reduce the overall impact. Agriculture in the basin will also need to adapt. Farmers already deal with uncertain rainfall, and future conditions will make this variability even more challenging. Promoting drought resilient crops, improving

irrigation efficiency, and encouraging diversification can help farmers manage risk more effectively. These changes will play a key role in sustaining livelihoods in the basin. Future research should move toward linking water availability with water demand. This study focuses on how much water (runoff + baseflow) the basin can generate, but long-term sustainability depends on how different sectors use that water. Bringing together hydrological models with agricultural, domestic, and industrial demand will provide a more complete understanding of water stress.

Uncertainty across climate models also deserves careful attention. While this study uses multiple GCMs to capture a range of possible futures, planners should treat these results as a range of plausible outcomes rather than a single prediction. Finally, improving data and monitoring systems will strengthen both analysis and decision-making. Expanding observational networks, improving data quality, and using remote sensing can provide better inputs for models and reliable real-time information. Strong data systems will support better planning and faster responses to extreme events. Overall, the Pennar River Basin faces a future where managing variability matters more than managing averages. By capturing excess water during wet periods, preparing for longer droughts, and adopting flexible and forward-looking strategies, stakeholders can build a more resilient and sustainable water management system for the basin.

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## ANNEXURES

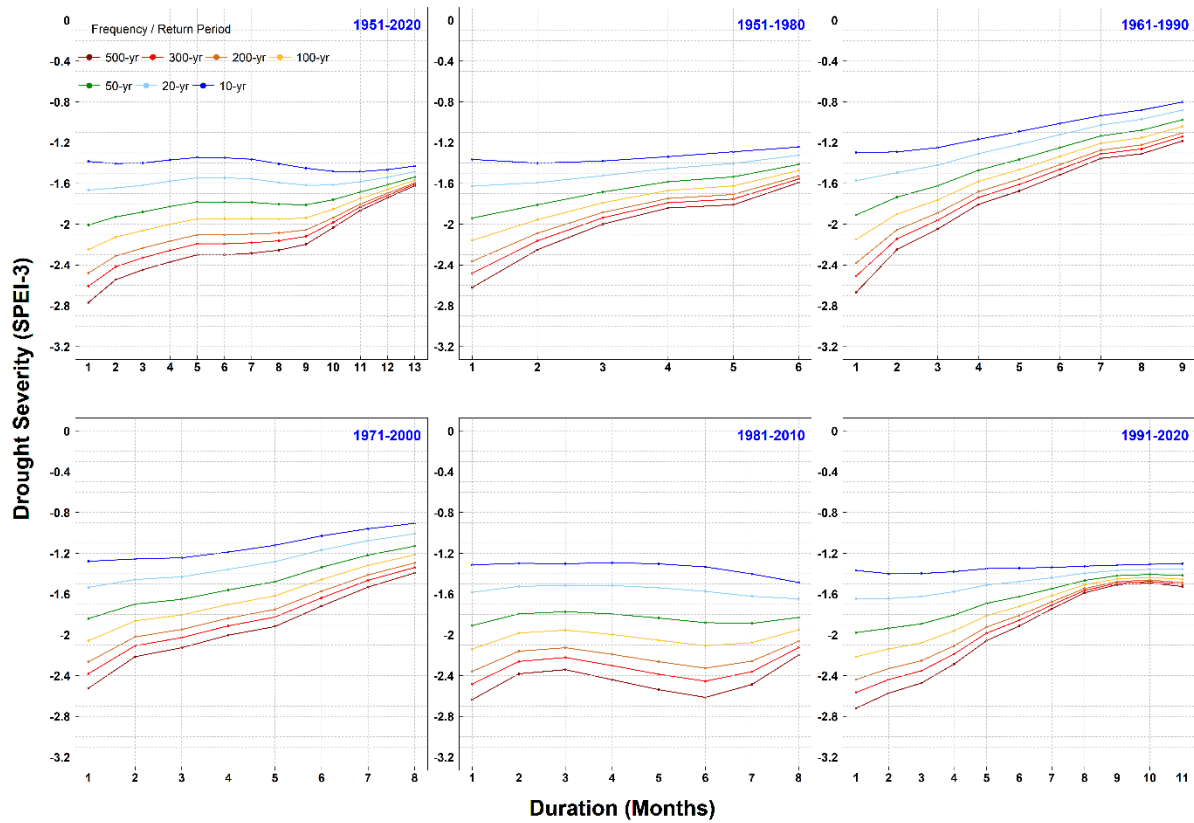


Figure S1 Severity-Duration-Frequency (SDF) curves based on the SPEI-1 index

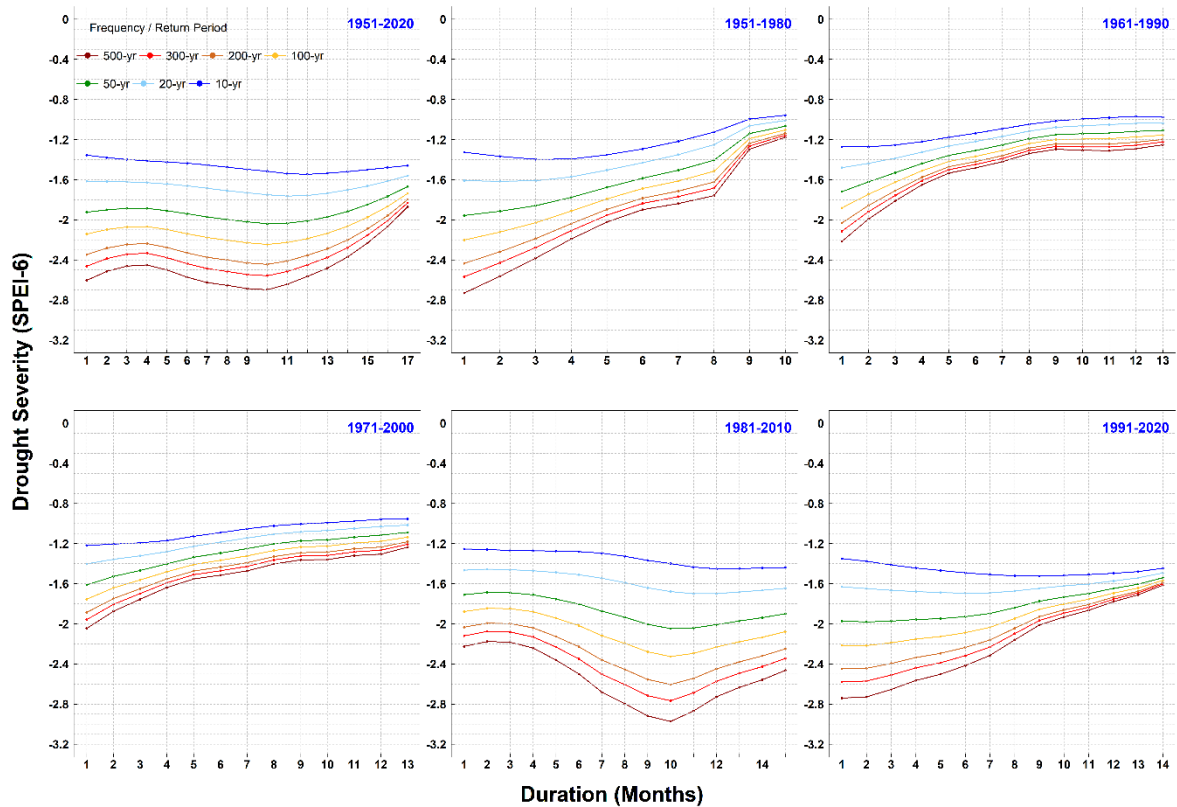


Figure S2. Severity-Duration-Frequency (SDF) curves based on the SPEI-3 index

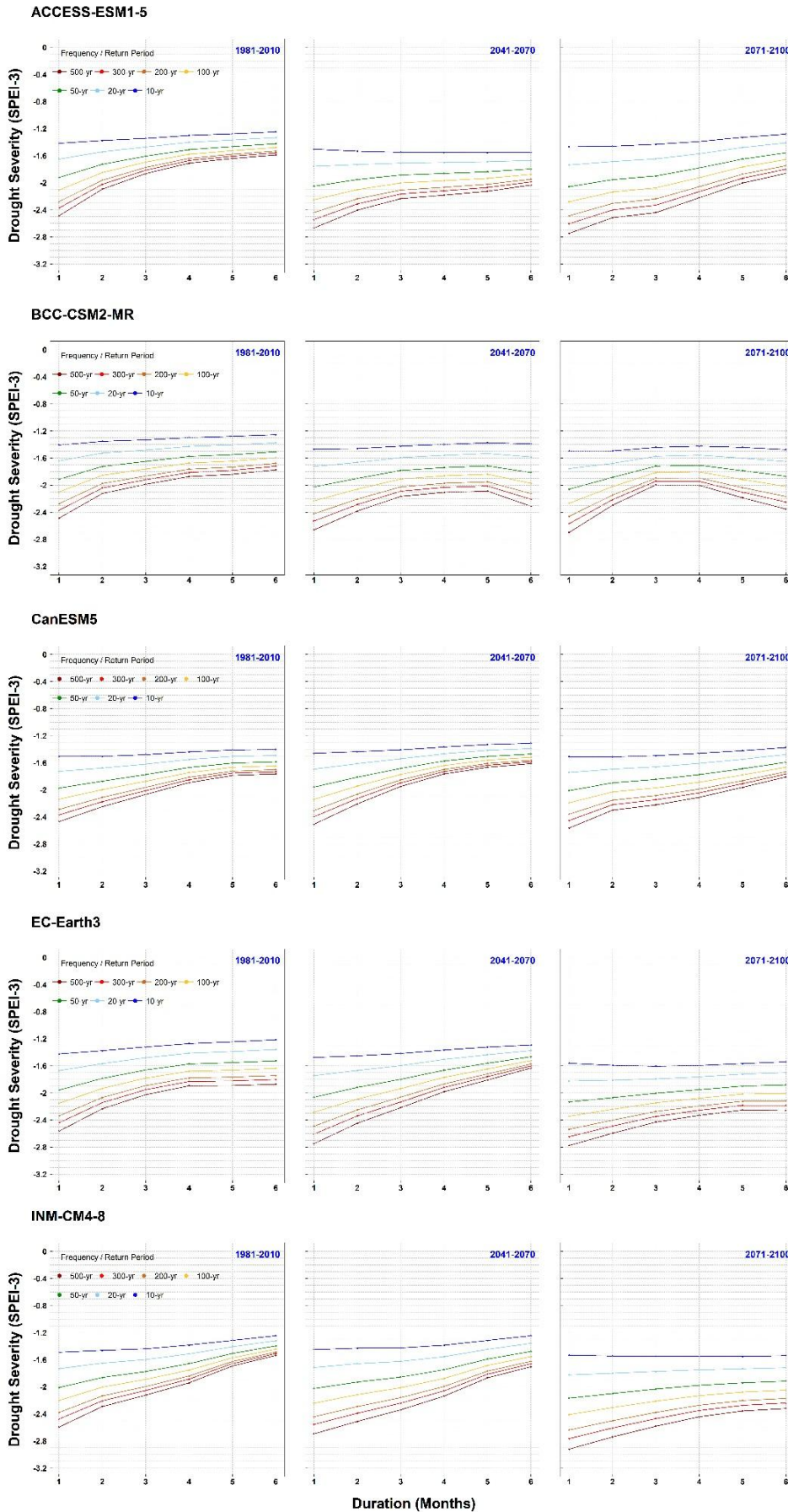


Figure S3. Severity-Duration-Frequency (SDF) curves based on the SPEI-3 index for the Pennar River Basin, derived from five GCMs (ACCESS-ESM1-5, BCC-CSM2-MR, CanESM5, EC-Earth3, and INM-CM1-8) for the historical baseline period (1981-2010) and two future periods: mid-century (2041-2070) and late-century (2071-2100) under SSP245 scenario.

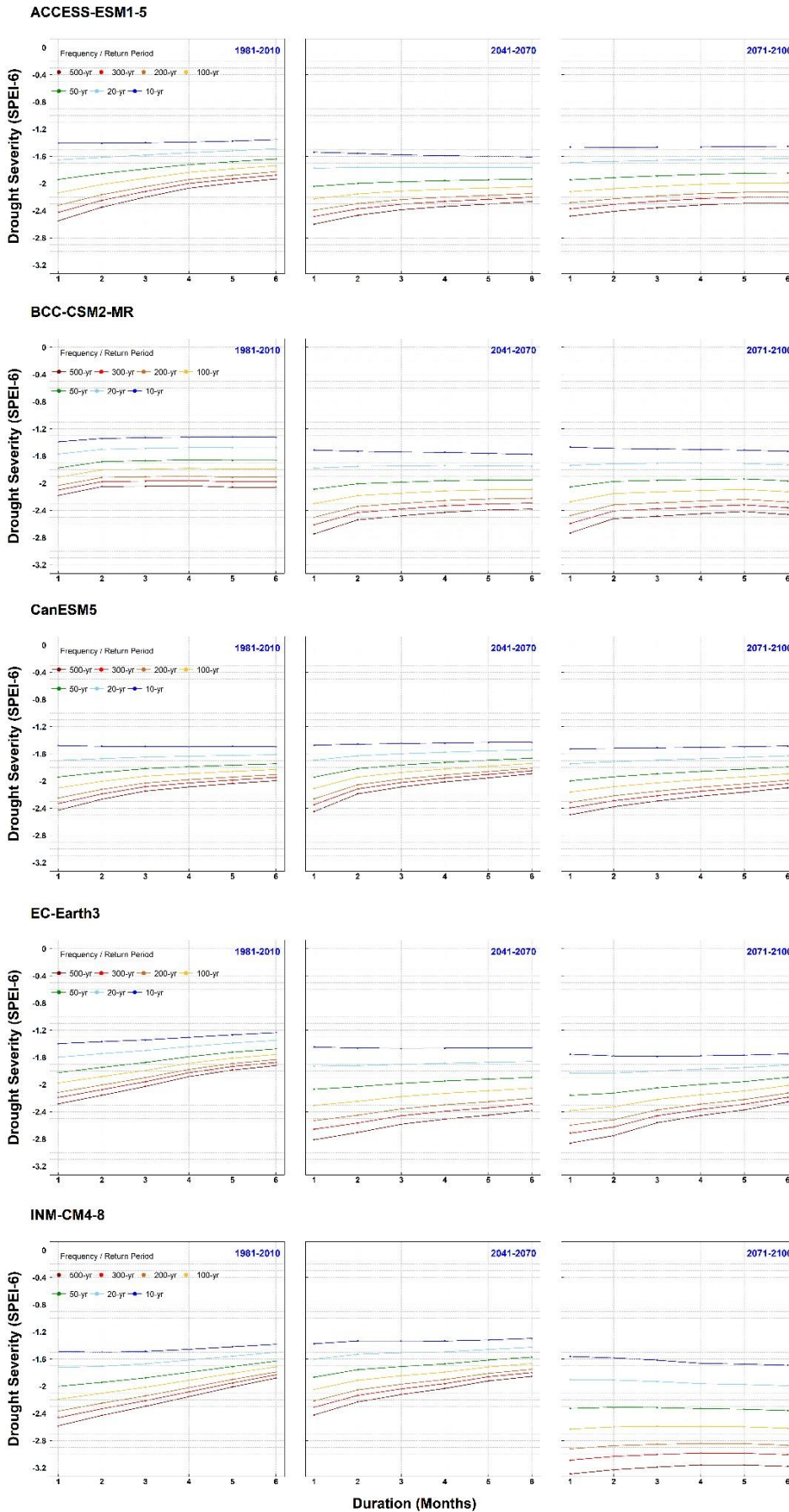


Figure S4. Severity-Duration-Frequency (SDF) curves based on the SPEI-6 index for the Pennar River Basin, derived from five GCMs (ACCESS-ESM1-5, BCC-CSM2-MR, CanESM5, EC-Earth3, and INM-CM1-8) for the historical baseline period (1981-2010) and two future periods: mid-century (2041-2070) and late-century (2071-2100) under SSP245 scenario



## **PUBLICATIONS FROM THE STUDY**

1. Das D, **Gurrapu S**, Singh D. 2025. Drought risk assessment in the Pennar River basin under changing climate: Severity-Duration-Frequency (SDF) based approach. 30<sup>th</sup> International Conference on Hydraulics, Water Resources, River and Coastal Engineering, HYDRO International – 2025, NIT Rourkela, Odisha. 18 – 20 December 2025. (*Paper ID – 114*)
2. Gurrapu S, Das D, Rao Y R S, Ramana R V. 2026. Assessment of Future Drought Risk in the Pennar River Basin using an SPEI-SDF Framework”, in *preparation to be submitted to the Journal of Water and Climate Change*

## SOFTWARE / DATA USED IN THE STUDY

This study uses a combination of observed meteorological data, climate model projections, and hydrological model inputs to assess drought characteristics and water availability in the Pennar River Basin. We used historical precipitation (0.25°) and temperature (1°) data from the India Meteorological Department (IMD) for the period 1951-2022. To maintain spatial consistency, we re-gridded the temperature data to match the precipitation resolution. For future climate conditions, we selected an ensemble of five GCMs under SSP245 and SSP370 scenarios. We used bias-corrected daily precipitation and temperature data for two-future periods – 2041-2070 and 2071-2100, to ensure reliable projections. We performed hydrological simulations using the VIC model (v4.2.d), based on the previously calibrated setup for the Pennar River Basin. We used land surface, soil, and vegetation parameters from the earlier study and generated key variables such as runoff, baseflow, evapotranspiration, and soil moisture.

We carried out all data processing, analysis, and visualisation in the R environment. We used SPEI package to compute drought indices and applied other packages for extreme value analysis. We handled spatial data processing and regridding using the terra package and related geospatial tools. Overall, this integrated use of high-quality datasets and well-established modelling tools provides a consistent and robust framework for evaluating drought dynamics and water availability under changing climate conditions.

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